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EXPERIMENTAL REPORT

NO. WAL 720/546

ARMOR PLATE - ROLLED

Ballistic and Metallurgical Properties of 12" SAM 1015 Rolled Homogeneous Armor Plate

BY

(1)

Watertown Arsenal Laboratory
Report No. WAL 710/546
Problem No. B2.6

26 October 1943

ARMOR PLATE—ROLLED

Ballistic and Metallurgical Properties of
1½" SAE 1035 Rolled Homogeneous Armor Plate

OBJECT

To determine the ballistic and metallurgical properties of four heats of SAE 1035 rolled armor.

CONCLUSIONS

1. Although the SAE 1035 rolled steels investigated passed the resistance-to-penetration requirements as of Specification AXS-488, they failed to possess satisfactory ductility under the impact of 75 mm. T21 proof projectiles.

2. The unsatisfactory shock resistance of SAE 1035 rolled steels of this thickness is correlated with the poor metallurgical properties, namely, inadequate hardenability, unsatisfactory microstructure and a low V-notch Charpy impact resistance.

3. This SAE 1035 rolled steel has a characteristic crystalline fracture which is associated with poor shock resistance.

E. L. Reed,
Research Metallurgist.

APPROVED:

H. H. ZORNIG,
Colonel, Ordnance Dept.,
Director of Laboratory.

[redacted]

INTRODUCTION

In accordance with a program on the conservation of alloys in rolled armor plate initiated in February 1942 by the War Production Board, an investigation was conducted at Watertown Arsenal to determine the ballistic and metallurgical properties of SAE 1035 rolled steel.

Attention should be called to the fact that since this investigation was undertaken, it has been determined at this Arsenal that good quality armor plate should possess adequate hardenability to quench out under the quenching conditions available. Hardenability studies made on SAE 1035 rolled steel indicate that 1½" thick plate of this type analysis has low hardenability and therefore cannot be quenched to the required initial hardness.

Three 1000-lb. heats of SAE 1035 steel were made at Watertown Arsenal and cast into ingots of the following sizes:

No. 539 - 10 x 12 x 30" with hot top
No. 1031 - 6 x 12 x 30" with hot top
No. 1032 - 6 x 12 x 30" with hot top

These ingots were slabbed and cross-rolled into plate approximately 25" x 26" x 1½" at the plant of the Henry Disston & Sons, Inc. Plate No. 539 was quenched in brine and not tempered at Watertown Arsenal while plates No. 1031 and 1032 were heat treated at Henry Disston & Sons, Inc., plate No. 1031 being spray quenched and not tempered, and plate No. 1032 being brine quenched and not tempered.

In addition, two straight-away rolled plates, 32 x 36 x 1½" plates, were obtained from the Youngstown Sheet & Tube Co. for this investigation. These plates were heat treated at the plant of Simonds Saw and Steel Co.; plate No. 1416 was spray quenched and tempered whereas plate No. 1417 was brine quenched and tempered.

The details on the casting of ingots, rolling the steel and heat treating the plates are given in Inclosure A.

TEST PROCEDURE

1. Ballistic Tests

Ballistic tests were made as follows:

a. Army ballistic limits were obtained on plates brine quenched and spray quenched with the 37 mm. APC M51 fired at normal.

b. Representative plates were subjected to the shock test using the 37 mm. TP M51 shot, 75 mm. AP T12 projectile with cap at 25° obliquity, the 75 mm. T21 proof projectile at normal, and the FTP test using the 37 mm. M51 APC shot, normal impact.

[redacted]

2. Metallurgical Examination

After completion of the ballistic tests, the plates were sectioned for a metallurgical study which included the following tests: chemical analyses, macroscopic examination, microscopic examination, Jominy hardenability tests, Brinell hardness tests and Rockwell "C" hardness surveys on cross-sections of the plates.

In addition, fracture tests were made on each plate for steel quality. Sections, 4" x 10", were nicked perpendicularly to the center of the longitudinal axis and broken slowly in a forge press.

Also, three standard V-notch Charpy impact bars and two .357" diameter tensile bars were machined from each plate. These test bars were taken halfway between the surface and the center and parallel to the plate surfaces.

RESULTS AND DISCUSSION

1. Ballistic Tests

A summary of the ballistic tests is given in Table I.

Detailed firing records are contained in Appendix A.

The ballistic limits of the plates were between 1 and 98 feet-per-second in excess of the specified ballistic limits required in Specification AXS-488.

A survey of the results of the shock tests indicate that this type of steel may pass the 75 mm. AP shock test. On the other hand, this steel is brittle under the impact of the 75 mm. T21 slug. One cross-rolled plate, No. 1032, and one "straight-away" rolled plate were subjected to the PTP test using the 37 mm. APC M51 shot. The cross-rolled plate behaved satisfactorily while the "straight-away" rolled plate spalled excessively under this test. The cross-rolled plate, No. 1032, was subjected to the shock test on a clear area of the plate with 75 mm. T21 proof projectiles after the PTP test had been made. Although the fracture occurred through previous impacts, it is believed that this armor would not have met the shock requirements under Specification AXS-488.

Cross-rolled plate, No. 539, showed good ductility under the impact of 37 mm. TP M51 shot.

The ballistic properties of the brine quenched plates were not superior to the water quenched plates.

2. Metallurgical Examination

a. Chemical Analysis

The chemical compositions of the test plates are given in Table II.

TABLE I

Summary of Ballistic Tests of

SAE 1035 Experimental 1½" Rolled Armor

Size of Plates, Nos. 539 - 21x35½x1½" - Tested at Watertown Arsenal and Aberdeen Proving Ground, ref. W.A. Firing Records #1 and #2, APG Firing Record #A4069.

1031 - 27x36x1½" - Tested at Aberdeen Proving Ground, ref. APG Firing Record #A5740.

1032 - 27x36x1½" - Tested at Aberdeen Proving Ground, ref. APG Firing Record #A5740; APG Report AD-523.

1416 - 32x36x1½" - Tested at Aberdeen Proving Ground, ref. APG Firing Record #A5740.

1417 - 32x36x1½" - Tested at Aberdeen Proving Ground, ref. APG Firing Record #A5740.

		Ballistic Properties					
			Shock Test		PTP Test		
Plate No.	Thickness Inches	Ballistic Limit F/S 37 mm. APC M51	75 mm. AP T12 with Cap 25° Obliquity	75 mm. T21 Proof Projectile Normal	37 mm. APC M51 Striking Velocity	Reported Brinell Hardness	Remarks
539 Brine Quenched not Tempered	1.548	1554 (+14)* 1541 (+1)	925 f/s HP CK	-	-	187	Satisfactory under 75 mm. AP shock test.
1031 Spray Quenched not Tempered	1.5	-	-	2?2 f/s LC Broke into two pieces.	-	217	Unsatisfactory
1032 Brine Quenched not Tempered.	1.54	1619 (+87)	-	1253 f/s LC Broke into two pieces.	2501 f/s BS 2-1/8x2-1/8", one petal.	207	Unsatisfactory
1416 Spray quenched and tempered	1.5	1598 (+98)	-	-	2524 f/s BS 3-5/8x3-5/8".	228-235	Unsatisfactory
1417 Brine quenched and Tempered	1.5	-	-	1226 f/s LC Broke into five pieces.	-	241-262	Unsatisfactory

*Numbers in parentheses indicate feet-per-second in excess of Specification AXS-488.

TABLE II

Chemical Analyses

Plate No.	C	Mn	Si	S	P	Cr	Ni	Cu	Al
539	.35	.80	.018	.021	.008	.08	-	.075	-
1031	.35	.84	.235	.022	.008	.05	trace	.085	.022
1032	.39	.91	.315	.022	.007	.05	trace	.09	.03
1416	.30	.98	.23	.031	.017	-	-	-	-
1417	.30	.98	.23	.031	.017	-	-	-	-

b. Macroscopic Examination

Figure 1 illustrates the macrostructure of the plates after the deep acid etch.

The cross-rolled plates, Nos. 539, 1031, and 1032, are relatively free from segregation. The "straight-away" rolled plates, Nos. 1416 and 1417, contain an appreciable amount of elongated nonmetallic inclusions.

c. Microscopic Examination

Typical segregation of nonmetallic inclusions found in the plates and also representative microstructures of the brine and spray quenched plates are shown in Figure 2.

An occasional series of disconnected fine nonmetallic inclusions were found in the central layers of each plate. These inclusions appeared to be small oxides and alumina. In all cases, as might be expected, pronounced grain boundary ferrite which was rejected during the quench surrounded grains of fine pearlite. This type of structure is generally associated with a low hardenability of the steel and poor shock resisting properties as verified in the plates tested.

The grain size of the plates is reported below:

Plate No. 539 - duplex grain size ASTM 5-9
Plate No. 1031 - duplex grain size ASTM 6-9
Plate No. 1032 - duplex grain size ASTM 6-9
Plate No. 1416 - duplex grain size ASTM 6-8
Plate No. 1417 - duplex grain size ASTM 8-9

d. Jominy Hardenability Test

The results of the end-quench hardenability tests which are shown in Figure 3 indicate that the rolled SAE 1035 steels investigated have inadequate hardenability for good quality armor plate. In fact, end-quench hardenability data indicated that these steels hardened only to a depth of less than 2/16" at a hardness level of 42 Rockwell "C".

e. Fracture Tests

The fractures of the SAE 1035 steels varied from nearly 100% crystalline to mixed fractures, that is, crystalline and fibrous. Such fractures are associated with a microstructure containing ferrite rejected on the quench and with poor shock resistance. Good quality armor, on the other hand, has been shown to possess a fibrous fracture which is associated with a microstructure consisting of spheroidized sorbite or tempered martensite and with resultant good shock resistance.

Some difficulty was experienced in the interpretation of the fractures for a steel quality rating due to the presence of large crystalline areas present. Crystalline[1] fractures tend to mask laminations present in the steel.

f. Mechanical Tests

(1) Brinell Hardness Determinations and Rockwell "C" Hardness Surveys

The results of the Brinell hardness determinations and Rockwell "C" hardness surveys are given in Table III.

TABLE III

Brinell Hardness and Rockwell "C" Hardness Surveys

Plate No.	Brinell Hardness Tests Made on Cross-Section at Watertown Arsenal		Average Rockwell C Hardness Made 1/16" apart on Cross-Section at Watertown Arsenal			
	Near Center	Near Surface	Near Center		Near Surface	
539 Brine Quenched not Tempered	183	183-187	6.5	9.5	9	12
1031 Spray Quenched not Tempered	170	167-187	6	8	6.5	13.5
1032 Brine Quenched not Tempered	197	201-207	11	13.5	14.5	16.5
1416 Spray Quenched and Tempered	212	192-212	15	17	10	18
1417 Brine Quenched and Tempered	217	235-248	17	19	27	45

The low Brinell hardness determinations are typical of normalized medium carbon steel and confirm the results of the microscopic examination in that plain medium carbon steel of this thickness cannot be quenched to a proper uniform initial hardness which is necessary in the heat treatment of good quality armor plate.

1. "Investigation of Heat Treating Variables Affecting the Quality of Nick Fractures" - Great Lakes Steel Corp., C. R. Schroder, 22 Mar. 1942.

3. Tensile Tests and V-Notch Charpy Impact Tests

The results of the tensile tests and V-notch Charpy impact tests are given in Table IV.

The steels have a fairly good combination of strength and ductility. The ductility of the straight-away rolled plates in the transverse direction is slightly lower than that of the cross-rolled plates in the same direction.

The V-notch Charpy values of this material are relatively low and are typical of poor quality armor, that is, containing rejected ferrite on the quench and poor shock properties.

Recently it has been determined that good quality rolled armor with a uniform microstructure of spheroidized sorbite had a V-notch Charpy value of approximately 100 foot-pounds in the longitudinal direction at a hardness of 270 Brinell.

SUMMARY

The ballistic limits of the SAE 1035 rolled steels, in several instances, compared favorably with those of some of the low alloy armor now in production. These results were confirmed in the testing of several SAE [2] 1035 cast plates of approximately the same thickness.

A PTP test made on a cross-rolled plate and "straight-away" rolled plate with the 37 mm. APC M51 shot indicated that the "straight-away" rolled plate showed greater spalling tendencies than the cross-rolled plate.

This type of material was very brittle under the impact of 75 mm. T21 proof projectiles.

The SAE 1035 rolled steel investigated has been found to have inadequate hardenability for good quality armor. A good correlation was obtained between unsatisfactory shock resistance of this steel and its poor metallurgical properties.

It was impossible by spray quenching or quenching in brine to obtain a proper uniform initial hardness which is necessary in the heat treatment of good quality armor plate.

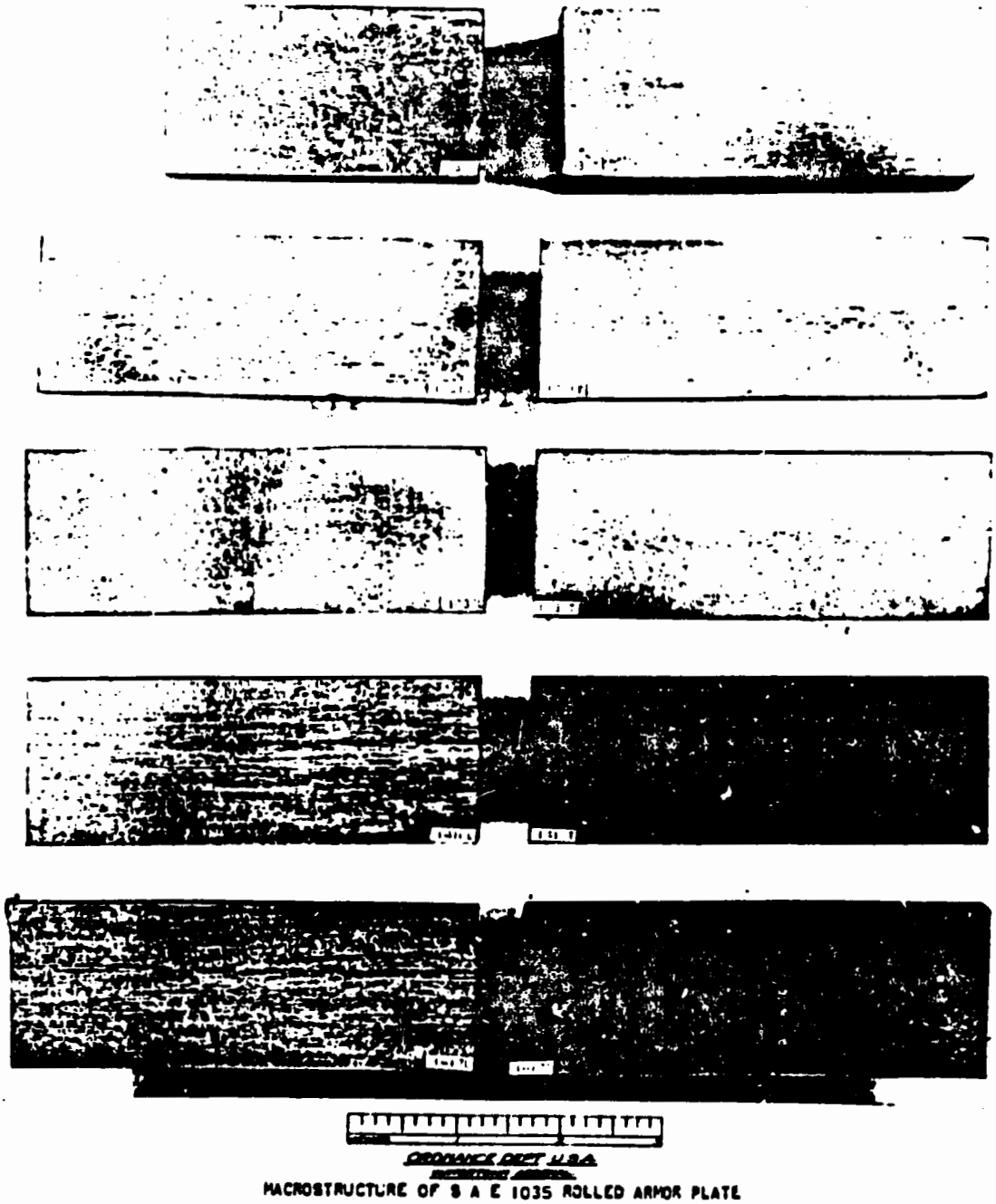
The ballistic properties of the brine quenched plates were not superior to the spray quenched plates.

2. Watertown Arsenal Report No. 710/457, June 30, 1943.

TABLE IV

Physical Properties of SAE 1035 Rolled Steel

Plate No.	Yield Strength Lbs/Sq.In.		Tensile Strength Lbs/Sq.In.	% Elong.	% Red. Area	V-Notch Charpy Ft/Lbs.	Brinell Hardness Determinations at Watertown Arsenal
539 Cross-rolled Brine Quenched not Tempered	Long.	50,000	98,000	22.9	58.9	61.7	183-187
	Trans.	48,500	97,500	24.3	61.7	37.3	
1031 Cross-rolled Spray Quenched not Tempered	Long.	59,000	92,800	28.3	63.9	66.4	167-187
	Trans.	55,300	92,000	24.7	54.0	55.1	
1032 Cross-rolled Brine Quenched not Tempered	Long.	71,000	104,800	23.6	58.3	54.2	197-207
	Trans.	68,000	104,800	23.6	62.8	38.2	
1416 Straight-away Rolled Spray Quenched and Tempered	Long.	68,300	107,500	21.8	59.9	34.4	192-212
	Trans.	71,800	105,800	21.4	45.3	26.4	
1417 Straight-away Rolled Brine Quenched and Tempered	Long.	---	112,000	20.0	52.0	49.7	217-248
	Trans.	---	105,500	20.0	44.3	26.4	

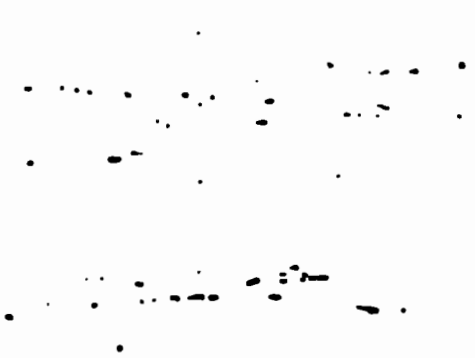


MACROSTRUCTURE OF S A E 1035 ROLLED ARMOR PLATE

NO. 539 W.A. CROSS ROLLED — BRINE QUENCHED. NOT DRAWN.
NO. 1031 W.A. CROSS ROLLED — SPRAY QUENCHED. NOT DRAWN.
NO. 1032 W.A. CROSS ROLLED — BRINE QUENCHED. NOT DRAWN.
NO. 1416 YOUNGSTOWN SHEET & TUBE CO. — STRAIGHTWAY ROLLED. SPRAY QUENCHED. DRAWN.
NO. 1417 YOUNGSTOWN SHEET & TUBE CO. — STRAIGHTWAY ROLLED. BRINE QUENCHED. DRAWN.
14 AUGUST 1943
WTN.71C-2137

FIG. 1

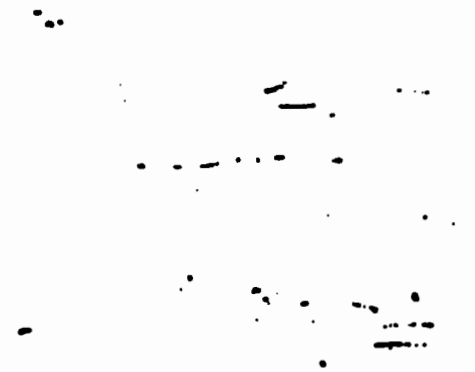
...and 1035 experimental 1" Rolled armor plate



X100 539 Unetched
Typical very disconnected non-metallic inclusions.

X1000 539 Picral
Ferrite and fine pearlite.

Brine quenched, no draw



X100 1031 Unetched
Typical disconnected non-metallic inclusions.

X1000 1031 Picral
Ferrite and fine pearlite

Spray quenched, no draw.

X100 1417 Unetched
Typical segregation of fine elongated non-metallic inclusions.

X1000 1417 Picral
Ferrite and fine pearlite.

Brine quenched, drawn at 500°F.

FIG. 2

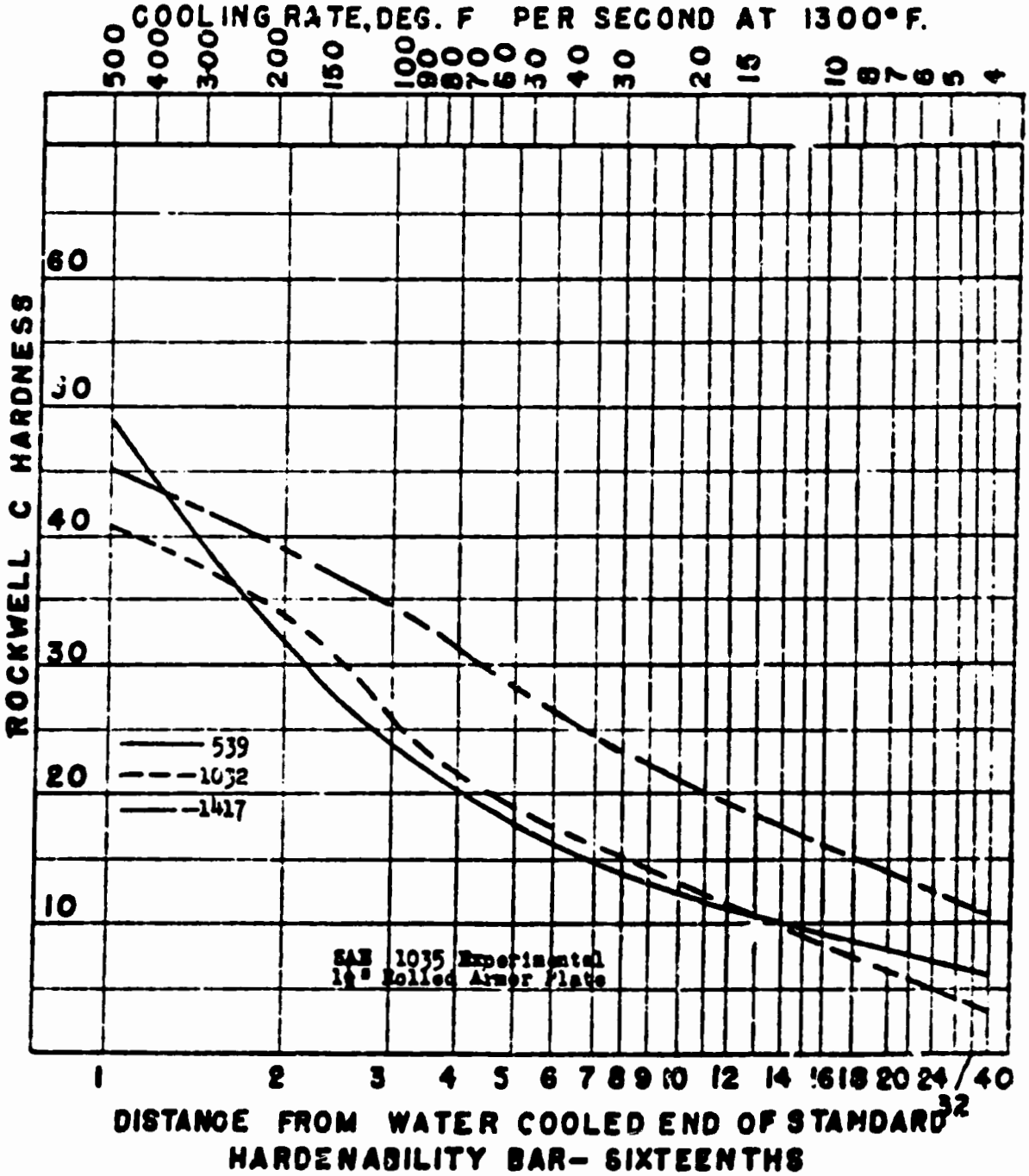


PLATE NO.	HEAT NO.	C	MN	SI	S	P	NI	CR	MO	Cu	Al	QUENCH TEMP. °F.	TIME	
539	———	.33	.76	.185	.016	.009	-	-	-	-	-	1600	2hrs.	
1032	— — —	.39	.91	.315	.022	.007	Tr	.05	-	.09	.03	1600	2hrs.	
1417	———	.30	.98	.23	.031	.007	-	-	-	-	-	1600	2hrs.	

FIG. 3

INCLOSURE A

INCLOSURE A

Melting Procedure

Three 1000-lb. heats of SAE 1035 steel were melted in an acid lined induction furnace and deoxidized with 1½-2lbs. of aluminum per ton. The heats were cast into ingots of the following sizes:

No. 539 - 10 x 12 x 30" with hot top
No. 1031 - 6 x 12 x 30" with hot top
No. 1032 - 6 x 12 x 30" with hot top

Slabbing of Ingots and Rolling into Plates

Ingots Nos. 539, 1031 and 1032 were slabbed and rolled into 1½" thick plate at the plant of Henry Disston & Sons, Inc. as noted below:

Ingot No.	Size of Plate	Final Rolling Temperature	Annealing Temperature after Final Rolling
539	35x21x1½"	2200°F	1200°F at temperature for 10 hrs.
1031	36x27x1½"	2256°F	1200°F at temperature for 2 hrs.
1032	36x27x1½"	2240°F	1200°F at temperature for 2 hrs.

Heat Treatment of Plates

Plate No. 539 was heat treated at Watertown Arsenal. Plate Nos. 1031 and 1032 were heat treated at the plant of Henry Disston & Sons, Inc. while plate Nos. 1416 and 1417 were heat treated at the plant of Simonds Saw and Steel Co.

Plate No.	Quench Temperature	Quench Media	Draw	Reported Brinell Hardness
539	1600°F - 3 hrs.	8% Brine	None	187
1031	1575°F	Water Spray	None	217
1032	1575°F	*Brine	None	207
1416	1600°F - 2 hrs.	Water Spray	500°F - 2 hrs.	228-235
1417	1600°F - 2 hrs.	*Brine	500°F - 2 hrs.	241-262

*Saturation of brine not stated.

Ballistic Data Sheet No. 1

Cross-Rolled Plate No. 539 - Size 21x35½x1½"

Brine Quenched not Tempered

Ref. W.A. Firing Records No. 1 and 2, 11, 13 July 1942.
Ref. APG Firing Record No. A4069, 8 Aug. 1942.

Plate Rd. No.	Powder Charge	Striking Velocity	Results
37 mm. APC M51 Firings:			
1	2.7 oz.	1627	CP 1/4" x 1/4".
2	2.6 oz.	1573	CP 1/8" x 3/16".
3	2.50 oz.	1558[a]	CP 1/8" x 1/2".
4	2.40 oz.	1524[a]	PP MB
5	5.80 oz.	2313	CP PTP 1-1/4" x 1-3/8". Full petalling.
6	2.35 oz.	1526	PP Backed by support.
7	2.40 oz.	lost	PP LB
8	2.50 oz.	1578	PP Backed by support.
9	2.50 oz.	1575[b]	CP 1/2" x 1/4".
10	2.40 oz.	1532	PP MB
37 mm. TP M51 Firings:			
11	6.5 oz.	2502	PP Punching started. Base intact.
75 mm. AP T12 (with Cap) Firing - 25° Obliquity			
1	10.30 oz.	925	PP Depth penetration 1-3/4". 2-1/4" horizontal crack on LB.

[a] Ballistic Limit - 1541 f/s

[b] Ballistic Limit - 1554 f/s

PLATE SATISFACTORY

Ballistic Data Sheet No. 2

Cross-Rolled Plate No. 1031 - Size 36x27x1½"

Spray Quenched, not Tempered

Ref. APG Firing Record No. A5740, 27 Jan. 1943

Plate Rd. No.	Powder Charge	Striking Velocity	Results
75 mm. T21 Proof Projectile Firing:			
1	18.35 oz.	1272	CP Plate broke into two pieces.

PLATE UNSATISFACTORY

Ballistic Data Sheet No. 3

Cross-Rolled Plate No. 1032 - Size 36x27x1½"

Brine Quenched not Tempered

Ref. APG Firing Record No. A5740, 27 Jan. 1943
Ref. APG Report No. AD-523, 23 May 1943.

Plate Rd. No.	Powder Charge	Striking Velocity	Results
37 mm. APC M51 Firings:			
1	2.90 oz.	1730	CP nose through 15/16". Open SC on LB.
2	2.65 oz.	1578	PP depth of penetration 1-15/16". SC on MB.
3	2.88 oz.	1645	CP nose in plate. SC on LB.
4	2.71 oz.	1593[a]	PP Depth of penetration 1-15/16". SC on LB.
5	6.95 oz.	2501[a]	CP BS 2-1/2 x 2-1/8". PTP. One petal.
75 mm. T21 Proof Projectile Firing Normal.			
1		1253[b]	Plate broke into two pieces. Fracture occurring through previous 37 mm. M51 APC impacts.

[a] Ballistic Limit 1619 f/s

Fracture of plate was crystalline. While the fracture occurred through previous impacts it is believed that this armor would not have met the shock requirements under Specification AXS-488.

PLATE SATISFACTORY FPP TEST, FAILED ON SHOCK.

BALLISTIC DATA SHEET NO. 4

"Straight-away" Rolled Plate No. 1416 - Size 36x32x1½"

Spray Quenched and Tempered

Ref. APG Firing Record No. A5740, 27 Jan. 1943

Plate Rd. No.	Powder Charge	Striking Velocity	Results
37 mm. APC M51 Firings:			
1	2.75 oz.	1646	CP daylight through large opening. Open SC on LB.
2	2.65 oz.	1582	PP depth of penetration 1-7/8". SC on MB.
3	2.70 oz.	1614[a]	CP daylight through small crack - Transverse crack on MB.
4	6.95 z.	2524[a]	CP diameter of penetration including BS 3-5/8" x 3-5/8". PTP.

[a]Ballistic Limit - 1598 f/s

PLATE FAILED PTP TEST

BALLISTIC DATA SHEET NO. 5

"Straight-away" Rolled Plate No. 1417 - Size 36x32x1½"

Brine Quenched and Tempered

Ref. APG Firing Record No. A5740, 27 Jan. 1943

Plate Rd. No.	Powder Charge	Striking Velocity	Remarks
75 mm. T21 Proof Projectile Firing - Normal			
1	18.35 oz.	1226	CP plate broke into five pieces.

PLATE FAILED ON SHOCK TEST